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MODULATION

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MODULATION

MODULATION OF A LOW FREQUENCY CARRIER WAVE

BY

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An investigation carried out under the direction of Dr. H. J. MacLeod.

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Modulation of a Low Frequency Wave

Introduction

In Modern broadcasting, signals can be transmitted from station to station only by the use of high frequency waves which radiate energy and are called carrier waves. Speech and music are sent over wires from the studio to the station in a manner similar to that used in an ordinary telephone system. The currents in the wires have frequencies that are the same as the frequencies present in the music and speech, and are therefore in the audio range. Currents with such low frequencies radiate practically no energy. They are, therefore, used to modulate the high frequency wave that is generated in the station. This high frequency wave radiates energy and carries with it, as a variation in amplitude, the low frequency modulating wave, which is the wave of speech or music.

The frequency of this carrier is fixed for any one station. The broadcast band of carrier frequencies extends from 550 K.C. to 1500 K.C.* and is divided into channels of 10 K. C. width, corresponding to frequencies of 550, 560, 570 etc., up to 1500 K. C. Each station is allotted one of these frequencies to be used as its carrier frequency.

If we represent the carrier wave by $A \cos \omega t$ and assume that it is being modulated by an audio frequency sine wave $B \cos \Omega t$, then the resultant wave will be of the form

$$(A + B \cos \Omega t) \cos \omega t$$

*K.C. = Kilocycles per second.

which through a simple trigonometric transformation becomes,

$$A \cos \omega t + \frac{B}{2} \cos (\omega + \Omega) t + \frac{B}{2} \cos (\omega - \Omega) t$$

This wave may be looked upon as three waves; the original carrier wave, together with two sidebands differing in frequency from the carrier (above and below) by an amount equal to the frequency of the modulating wave.

The various circuits of a station are turned to the carrier frequency, and hence will not respond to the same extent to the sideband frequencies unless special provision is made for this. The circuit can be arranged however, so that nearly the same antenna current (response) is obtained at a number of different frequencies. Thus it is possible to obtain very nearly equal response to the carrier frequency and to frequencies in the range covered by the sidebands. This can be done by the use of coupled circuits, which can be designed to give a resonance curve with a flat top.

The literature on the subject however, does not appear to contain any very definite experiments with resonant circuits showing the effect of unequal response on the percentage modulation, and the amplitude of the sidebands. The response referred to here is that obtained by the use of modulating voltages of different frequencies but with constant amplitude. It was the purpose of this investigation to make a study of the case as outlined above.

Selection of Frequencies

Ordinary broadcasting, as mentioned before, is done with carrier frequencies ranging from 550-1500 K.C. High frequencies of this order are called Radio Frequencies, and when used in circuits exact measurements are difficult, due to their complicated behavior. There are many advantages in carrying out the investigation with a carrier wave of low frequency. The process of modulation will take place the same as if a high frequency carrier were used, but it may be studied without some of the difficulties encountered in high frequency measurements. Oscillograms of the modulated wave forms may be obtained by an ordinary oscillograph, operated in synchronism with the source of the modulating wave. Stray capacities and inductances are negligible compared with the comparatively large values required in the resonant circuits. Voltages and currents can be obtained by means of standard meters. The various circuits were therefore designed for a carrier frequency of 512 cycles per second. This particular frequency was selected because it is the frequency of one of the standard tuning forks, and hence the frequency of the oscillator could be checked. A frequency of this order was the lowest for which resonant circuits could be conveniently built, and about the highest that could be used successfully with the oscillograph, for wave analysis.

The frequency of the modulating waves was selected so that they would bear the same ratio to the carrier frequency as they do in ordinary radio frequency broadcasting.

These modulating waves, in ordinary broadcasting, correspond to the audio range, and vary in frequency from 50 to 10,000cycles per second, while the carriers vary from 550 to 1500 K. C.

Since in this experiment the carrier has been reduced to about one one-thousandth of its normal radio frequency value, the modulating waves should be reduced in about the same proportion, The range actually used was from 4 to 20 cycles per second.

Description of the Circuit

The circuit shown in fig. 1 was finally adopted after considering and discarding many others. It is really the circuit of a complete transmitter operating with a carrier frequency of 512 cycles, and consists of an oscillator, a power amplifier and a modulator. Modulation is of the plate circuit or Heising type, and takes place in the power amplifier. We are interested principally in this modulated power amplifier and its output circuit.

Power Amplifier

Tube A is the power amplifier tube. It is biassed to cut-off, and obtains its grid excitation from the oscillator as shown. It feeds the tank circuit L_1 C_1. This tank circuit is tuned to resonance by the variable condenser C_1. This is done by isolating the tank circuit, inducing an E.M.F. alterneting at 512 cycles, and tuning for maximum current.

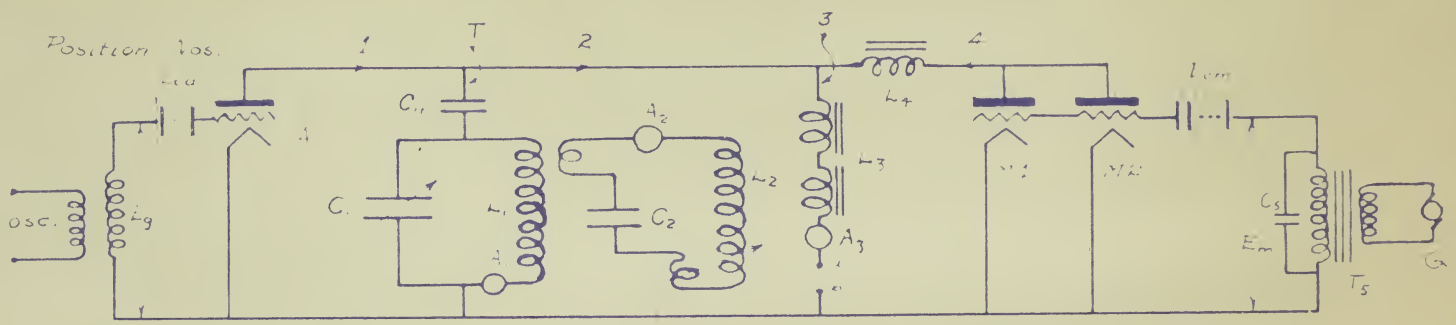
Coupled to the tank circuit is the antenna circuit L_2 C_2 , which is tuned to resonance by the vario-coupler as shown. C_{11} is inserted to prevent a short circuit of the plate supply.

Modulators

M1 and M2 are the modulator tubes. They are biassed to operate on the straight portion of the tube characteristic. The modulating wave is obtained from one phase of the alternator shown.

C_5 is a smoothing condenser.

Fig. 1. Modulation Circuit



Constants.

C_1	.737*	L_1	.1320	E_{co}	−47.0
C_1'	1.0	L_2	.0467	E_{cm}	−21.7
C_2	1.0	L_3	308C.	T_5	1.5 Ratio 4 KVA Distribution Trans
C_5	18.0	L_4	12.4	A_1 A_2	R.F. Ammeters.
Res. of $C_1 + L_1 + A_1$		R_1'	= 8.4	A_3	D.C. Milliammeter
$C_2 + L_2 + A_2$		R_2'	=	L_3	11 T windings of 2 5 KVA Trans.

G is a slow driven 9 KVA Alternator 13200 − 220 v Ratio Res 874.0

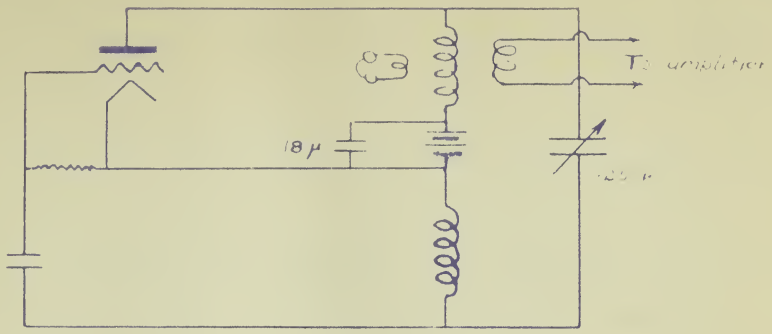
L_2 is the total L.a of Ant. circuit

Power Supply is connected at a.b.

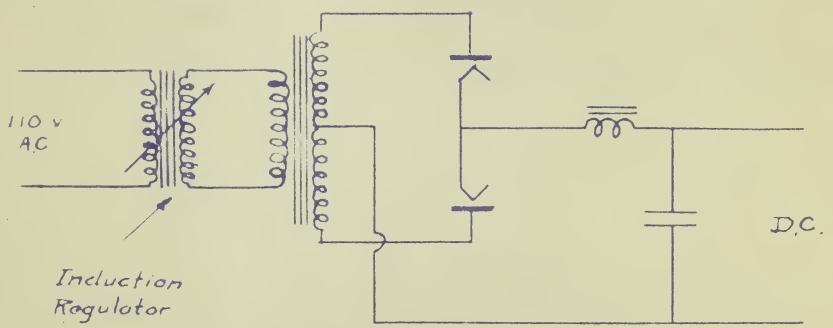
*The units used are ohms, microfarods and heneries.

Fig. 2.

Oscillator



D.C. Power Supply



Description of the Circuit (Continued)

The Oscillator

The oscillator is shown in fig. 2. It is of the Hartley type. The frequency of the oscillator can be heard as a note in the phones, and can be set at 512 cycles by means of a tuning fork. The fork is held near the phones, and the circuit tuned until no beats are present. Other frequencies were obtained by changing the value of the condenser in the oscillating circuit, by means of a decade condenser.

PART 1

DESIGN OF THE POWER AMPLIFIER AND ITS OUTPUT CIRCUIT

The main requirements in this circuit were :-

1. Minimum distortion.
2. A high plate circuit efficiency.
3. A high efficiency of power transfer from tank to antenna.
4. A suitable band width.
5. A suitable decrement.

These requirements will now be considered.

In order to obtain minimum distortion the tubes were operated over the correct part of their characteristic curves. (Tube A is to operate as a class B amplifier). It is also necessary to have a driver that can supply sufficient power to drive the grids positive without distortion. Harmonics introduced by tube operation will flow through the low impediance path C_{11} , and not enter the antenna circuit.

A high plate circuit efficiency is obtained by operating the tube A as class B, and by selecting the proper value of load impedance to work with a given value of tube impedance.

The efficiency of power transfer from tank to antenna is $\frac{W^2 M^2}{W^2 M^2 + R_1 R_2}$. This transfer efficiency can be made high by making $W^2 M^2$ large, or $R_1 R_2$ small; keeping in mind that such changes may cause other effects in the circuit.

The band width must be wide enough so that high notes will not be attenuated, and narrow enough so that there will be no interference in other wave channels. Such a band width is secured by means of a coupled circuit. The tank circuit is coupled to the antenna circuit and the band width can be adjusted by changing the amount of the coupling. A large inductance will cause a wide band of frequencies to be transmitted without attenuation.

The decrement of the antenna circuit is

$$\delta = \frac{R}{2 f L} ,$$

where f is the carrier frequency, and R and L refer to the antenna circuit.

The decrement must be large enough to ensure good quality over the audio band that is being transmitted without distortion. This requirement is always fulfilled in a circuit with low carrier frequency.

The ratio $\frac{R}{L}$ is large in the circuit that is being used in this work. Modulation may take place at a high power level or a low power level. If it takes place at a low power level, the plate circuit efficiency is not an important factor, so the chief concern is to obtain minimum distortion due to the modulation characteristics of the circuit. In the Heising system this means a linear relation between output current and plate voltage. To obtain this it is necessary to have a large plate impedance, sometimes of the order of the tube impedance. If modulation takes place at a high power level, this selection of the load impedance effects the output. A high output is important, and this is often accomplished by the choice of a smaller load.

Part 1. (Continued)

For class "B" operation the impedance of a tube is not constant over a complete cycle of the wave impressed on the grid. It is infinite over the part of the cycle when there is no plate current flowing. Considering the whole cycle, or a number of cycles, there will be an overall impedance, or an effective impedance, as it is called. This can be used for circuit calculations where instantaneous values are not required. For class "B" operation the effective tube impedance is approximately twice the ordinary A.C. tube impedance.

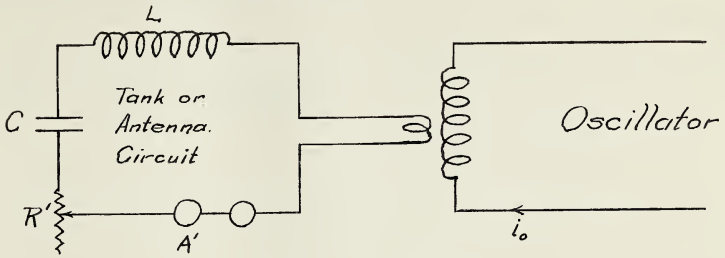
The value of the load impedance will be determined by the kind of circuit, and the effective tube impedance, as indicated in the preceding note.

All the requirements stated above are interdependant. A large number of the values of resistance, inductance, capacity etc. are variables which depend on each other. Some of these values vary according to relations which must be found experimentally. For this reason the best values of the circuit constants, as we shall call them, can be determined only approximately by theory. The circuit should be tested experimentally with different values before decisions are finally made. This was actually done in the circuit used here. The values finally selected are shown in Fig. 1.

Part 3

MEASUREMENT OF RESISTANCE

Measurement of the resistance in the tank and antenna circuits (this includes the resistance of the coil, the condenser, and the meter). All resistances were measured using alternating current at 512 cycles.



A circuit was arranged as shown in the diagram. A variable resistance R′ and an additional meter A′ were placed in the circuit. R′ was set at zero. The circuit was tuned to resonance at 512 cycles, and a reading obtained on A′ = I_a. Resistance equal to R was then added to the circuit by adjusting R′, until the current dropped to a value equal to I_b; i_o was kept constant.

Then

$$R_x = \frac{R}{\frac{I_a}{I_b} - 1}$$

Thus R_x the value of the total resistance in the circuit was found.

The resistance at 512 cycles of the extra meter A′ was found by means of an A. C. bridge, and subtracted from the value found above, to obtain the true value of the resistance, for the for the circuit as actually used.

Tube Constants

The characteristic curves of the tubes were checked, and the plate impedance and the amplification factor of the tubes were found from these.

The values of all the constants are shown with the diagrams of the circuits.

PART 4

Circuit calculations - Theoretical.

Calculation of voltages and currents in the circuit, based on the values of the circuits constants as found in Part 3. The following notation will be used, -

V.T. = Vacuum tube.

R.F. = Radio frequency (Corresponding to 512$\sim$ here.).

η = Efficiency.

f = Frequency.

ω = Periodicity = $2\pi f$.

M = Mutual inductance (Between Tank and Antenna).

μ = Amplification factor of V.T..

R_p = Ordinary A.C. resistance of V.T. Approximately equal to the A.C. impedance at ordinary f ..

E_g = Effective A.C. volts induced on grid by osc..

E_m = Effective A.C. volts induced on grid by alternator (Shown in Fig. 1.).

I_p = Effective value of the fundamental component of the A.C. (512$\sim$) in the plate circuit of the amplifier. (Position 1.).

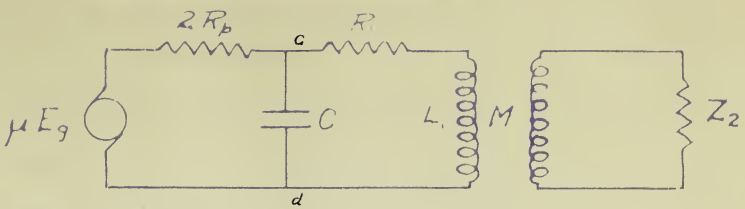
Osc.= Oscillator.

Subscript 1 refers to the tank circuit.
" 2 " " " antenna circuit.
" m " " " modulator circuit.

Fig. 3.

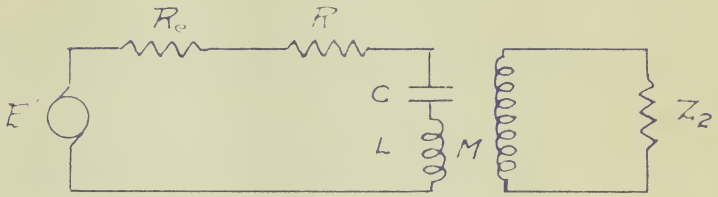
Circuit Reduction

(a)



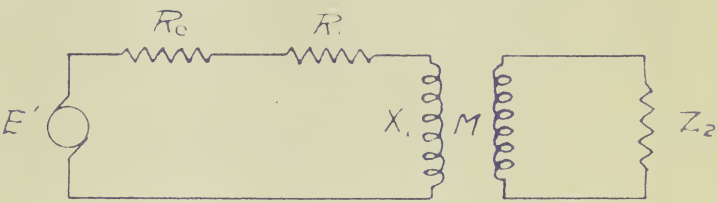
Use Thevenin's Theorem

(b)



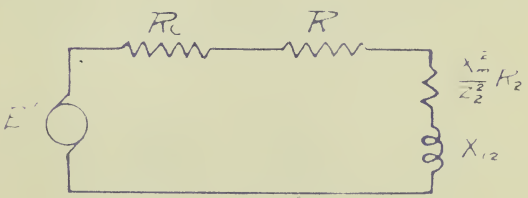
Combine L and C

(c)



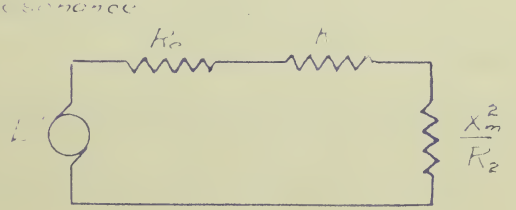
Transfer Secondary

(d)



At resonance

(e)



Part 4 (Continued)

Calculation of I_1 the effective value of the current in the tank circuit, and I_2 the effective value of the current in the antenna circuit. No modulation is taking place, but the modulator tubes are lit. The two currents will of course have a frequency of 512 cycles.

Since we are interested mainly in I_1 and I_2 we may replace the circuit of Fig. 1. by that of Fig. 3(a). We will later see that this is justifiable when we examine the relative values of current in the circuit of Fig. 1. In Fig. 3(a) we replace the tube by a generator with an effective tube impedance $2R_p$ in series.

The voltage of this generator will of course be μE_g. The equivalent impedance from c d looking back is equal to

$$Z' = \frac{2R_p X_c^2}{(2R_p)^2 + X_c^2} - jX_c$$

(By Thevenin's Principle)*

When $2R_p$ is large in comparison to X_c, as is the case here

$$Z' = \frac{X_c^2}{2R_p} - jX_c$$

Or

$$Z' = R_e - jX_c ,$$

and we get Fig. 3(b), where the generator and condenser C_1 have been replaced by an equivalent series circuit, consisting of $R_e - jX_c + (R_1 + j\omega L_1)$.

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* Communication Engineering - Everitt P. 333

Part 4 (Continued)

The voltage of the generator will change from μE_g to

$$E' = \mu E_g \frac{X_c}{\sqrt{(2R_p)^2 (X_c)^2}}.$$

When X_c is small compared to $2R_p$, this becomes

$$E' = \frac{\mu E_g X_c}{2R_p}.$$

The impedance of the series circuit in Fig. 3(b) is

$$R_e - jX_c + R_1 + jX_L.$$

Combining $jX_L - jX_c = X_1$,

We get for this impedance $R_e + R_1 + X_1$,

which is represented in Fig. 3(c).

Now if we transfer the secondary circuit to the primary circuit, we find that the secondary adds

$$\frac{\omega^2 M^2}{Z_2^2} R_2 - j \frac{\omega^2 M^2}{Z_2^2} X_2.$$

The equivalent series circuit (Fig. 3(d)) will therefore have an impedance

$$\left(R_e + R_1 + \frac{\omega^2 M^2}{Z_2^2} R_2\right) + j\left(X_1 - \frac{\omega^2 M^2}{Z_2^2} X_2\right).$$

At resonance, $X_1 = 0$ and $X_2 = 0$ and $Z_2 = R_2$ and the equivalent series impedance becomes a resistance equal to

$$R_e + R_1 + \frac{\omega^2 M^2}{R_2}. \qquad \text{Fig. 3(e).}$$

If we know E' and the equivalent series impedance, we can find

$$I_1 = \frac{E'}{\text{Impedance}}.$$

Part 4. (Continued)

The general solution of a two circuit network gives

$$I_2 = I_1 \frac{Z_M}{Z_2}.$$

At resonance this becomes

$$I_2 = I_1 \frac{\omega M}{R_2}.$$

The constants of the circuit as found in part 3 are:

$L_1 = 0.132$	$C_1 = 0.737$	$R_1 = 8.4$
$L_2 = 0.0967$	$C_2 = 1.0$	$R_2 = 11.0$
$M = 0.0071$	$C_{11} = 1.0$	$2R_p = 8200.$

The units are henries, microfarads and ohms.

Calculation of I_1 and I_2 at resonance.

Impedance of $C_1 = X_c = \frac{1}{2 \times \pi \times 512 \times .737 \times 10^{-6}} = 422.$

$$E' = \frac{\mu E_g X_c}{2R_p} = \frac{8.3 \times 65.0 \times 422.}{8200} = 27.9 .$$

If E_g is held at 65.0 volts,

The single equivalent impedance equals (Fig. 3e)

$$= \frac{X_c^2}{2R_p} + R_1 + \frac{\omega^2 M^2}{R_2}$$

$$= \frac{422^2}{8200} + 8.4 + \frac{(0.0071 \times 2\pi \times 512)^2}{11.0}$$

$$= 21.7 + 8.4 + 47.4$$

$$= 77.5 .$$

Part 4 (Continued)

$$I_1 = \frac{27.9}{77.5} = 0.360 \text{ amps.}$$

$$I_2 = \frac{0.360 \times 0.0071 \times 3215}{11.0} = 0.748 \text{ amps.}$$

The load on the amplifier tube is equal to the impedance of the parallel circuit (made up of C_1 and L_1 coupled to the antenna). This load impedance, by parallel circuit theory is equal to

$$R_L = \frac{L_1}{C_1 R_{12}}$$

$$= \frac{0.132}{0.737 \times 10^{-6} \times 55.8} = 3210. \text{ Ohms.}$$

$$I_p = \frac{\mu E_g}{2R_p + R_L} = \frac{8.3 \times 65.0}{8200 + 3210.}$$

$$= 0.0473 \text{ amps.} = 47.3 \text{ M.A.}$$

The voltage across the tank circuit is

$$0.0473 \times 3215 = 152.0 \text{ volts.}$$

To find the current in position 4.

Impedance of $L_4 = 2\pi f L_4 = 3215 \times 12.4 = 39800.$

(Ohms reactive)

Impedance of the two modulating tubes in parallel operating as class "A" $= \frac{4100}{2} = 2050.$

(Ohms resistive.)

Total impedance of L_4 and the tubes = 39800. Ohms.

(Tubes negligible)

Current in pos. 4. $= \frac{152. \times 1000.}{39800.} = 3.82$ M.A..

Part 4. (Continued)

Calculation of I_1 and I_2 for a frequency of 526 cycles.

This is chosen to show how the calculations are made when the circuit is not resonant, that is, a frequency other than the resonant freq. of 512 cycles is applied.

$$\omega = 3304.$$

$$X_{L1} = \omega L_1 = 3304 \times 0.132 = 436.0j$$

$$X_{C1} = \frac{1}{\omega C_1} = \frac{1}{3304 \times 0.737 \times 10^{-6}} = 410.6j$$

$$X_1 = 25.4j$$

$$X_{L2} = \omega L_2 = 3304 \times 0.0967 = 319.5j$$

$$X_{C2} = \frac{1}{\omega C_2} = \frac{1}{3304 \times 1.0 \times 10^{-6}} = 302.7j$$

$$X_2 = 16.8j$$

$$X_m = \omega M = 3304 \times 0.0071 = 23.47 \qquad X_m^2 = 550.$$

$$Z_2 = R_2 + jX_2 = 11.0 + j16.8 = 20.1 \angle \theta \qquad Z_2^2 = 403.0$$

$$\frac{X_m^2}{Z_2^2} R_2 = \frac{550 \times 11.0}{403.} = 15.02$$

$$\frac{X_m^2}{Z_2^2} X_2 = \frac{550 \times j16.8}{403.} = 22.94j$$

The single equivalent impedance is

$$\left(\frac{X_c^2}{2R_p} + R_1 + \frac{\omega^2 M^2}{Z_2^2} R_2 \right) + j \left(X_1 - \frac{\omega^2 M^2}{Z_2^2} X_2 \right).$$

$$Z_{12} = \left(20.5 + 8.4 + 15.02 \right) + j25.4 - j22.9$$

$$= 43.9 + j2.5$$

$$= 44.0 \angle \theta_2$$

Part 4. (Continued.)

$Z_{12} = 44.0$

$$E' = \frac{\mu E_g X_c}{2R_p + X_c} = \frac{540. \times 410.6}{8250} = 26.8 \text{ volts.}$$

$$I_1 = \frac{E'}{Z_{12}} = \frac{26.8}{44.0} = 0.611 \text{ amps}$$

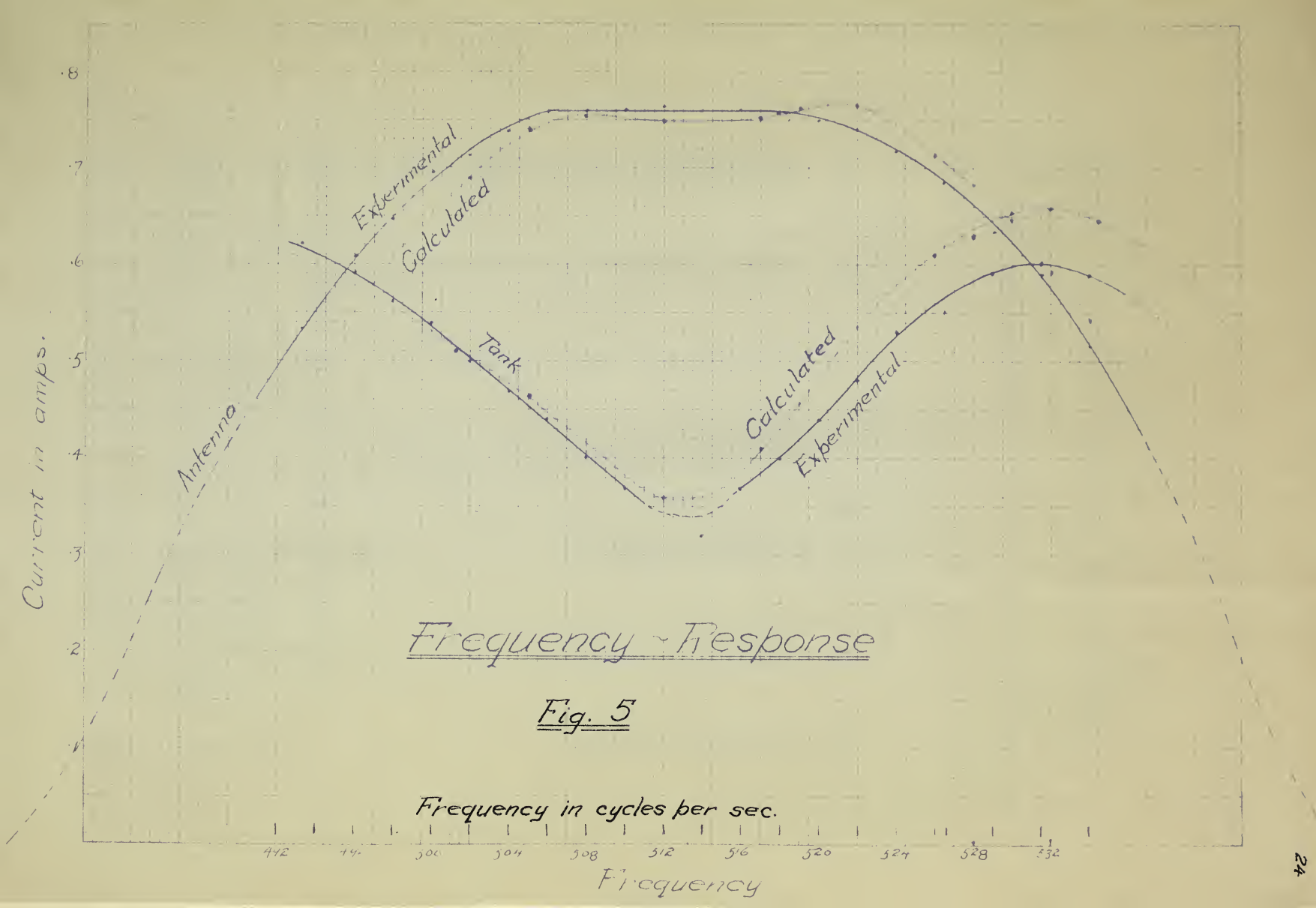
$$I_2 = I_1 \frac{Z_m}{Z_2} = 0.611 \times \frac{23.47}{20.1} = 0.712 \text{ amps.}$$

Part 5 EXPERIMENTAL WORK

The object of the experimental work was to adjust the circuit so that its frequency response curve corresponded to that of an ordinary broadcast transmitter, and to find the curve experimentally, to modulate the carrier with waves of different frequencies, and to find the effects produced on the sideband amplitude, and the percentage modulation.

In Fig.1 the tank circuit is coupled to the antenna circuit. A coupled circuit of this type is selective. By this we mean that it will respond to a greater extent to a certain band of frequencies than to any other frequencies. Since the circuit is a transmitter, response refers to the antenna current produced. A curve showing the antenna current produced when waves of different frequencies are impressed on the circuit by the oscillator, may be called a "Frequency Response Curve" or a "Transmission Characteristic."

Such a curve was found for the circuit used, by applying waves of different frequencies, but with the same amplitude, and measuring the antenna current produced. This curve was also calculated theoretically by the methods used in Part 4 of this



Frequency - Response

Fig. 5

investigation. The two curves shown in Fig. 5 together with similar curves for the current in the tank circuit.

The values obtained for the curves are shown in Table 1.

Table 1.

		Experimental		Theoretical		
Freq.	I_{dc}	I_1	I_2	I_1	I_2	Freq.
493.	82.	.62	.535	.505	.689	502
496.	78.	.59	.610	.466	.740	505
498.	78.	.56	.648	.401	.755	508
500.	80.	.54	.690	.360	.748	512
502.	82.	.50	.712	.410	.755	517
504.	82.	.47	.738	.458	.762	519
506.	83.	.44	.758	.535	.765	522
508.	88.	.40	.759	.611	.712	526
510.	88.	.37	.760	.627	.681	528
512.	90.	.36	.765	.656	.649	530
514.	90.	.32	.750	.657	.590	532
516.	88.	.37	.760	.647	.547	534
518.	87.	.40	.756			
520.	86.	.44	.748			
522.	85.	.48	.740			
524.	83.	.53	.718			
526.6	81.	.55	.685			
529.	79.	.59	.632			
531.5	78.	.60	.590			
534.	78.	.59	.518			

The constants for the circuit were:

Grid excitation E_g = 65.0 volts (Effective)

Grid Bias Amplifier tube -47.0 volts.

Modulator tube -21.5 volts.

Both amplifier and modulator tubes operating.

The constants for the circuit, (continued).

E_m = 0.

E_f = 7.5 volts. I_f = 1.25 amps. (Filament)

E_b = 440.0 - Drop in choke.

Resistance of choke = 874. ohms.

Theoretical and experimental values check as closely as can reasonably be expected, considering the nature of the circuit, and the conditions of Operation.

The wave spreads of the theoretical and experimental curves were found to be almost identical.

It should be noticed that the frequency response to the tank circuit was quite different to that of the antenna.

The frequency response curve of the antenna has a flat top, insuring true response to the important band of frequencies. It has a sharp cutoff, above and below the desired band.

By making use of the frequency response curve of Fig. 5 we shall proceed to explain the action of the circuit when a modulated wave is impressed on the tank circuit. When no modulation takes place, the current in the antenna circuit will be an alternating current with a constant amplitude , and with a frequency equal to that of the oscillator. A current of this type is shown in (a′) of Fig. 6d.

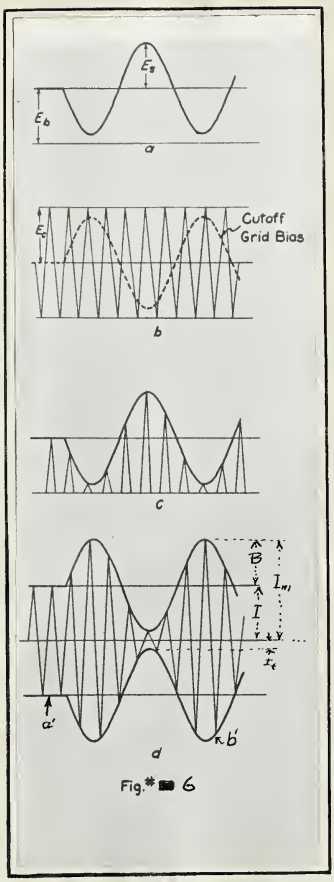


Fig.* 6

When no modulation takes place, the amplitude of the carrier will be varied as shown in (b′) of Fig. 6d. This variation should be of the same form as the modulating wave.

If ω is the periodicity corresponding to a frequency of 512 cycles per second(the carrier frequency), then the equation of the current in (a′) will be

$$I \cos \omega t \quad .$$

If the equation of the modulating wave is $B \cos \Omega t$, the equation of the current in (b′) will be

$$(I + B \cos \Omega t) \cos \omega t \quad ,$$

or, through a simple trigonometric transformation,

$$I \cos \omega t + \frac{B}{2} \cos (\omega + \Omega) t + \frac{B}{2} \cos (\omega - \Omega) t$$

This last equation may be interpreted by saying that a modulated radio frequency wave (R. F. wave) consists of three R. F. waves of constant amplitude, but differing in frequency from the carrier (above and below), by an amount equal to the frequency of the modulating wave. The first wave in the equation is called the carrier wave, and the two other waves are called side-bands. If the above interpretation is correct, the amplitude of the carrier is I , and the amplitude of each side band is $\frac{B}{2}$, where B is the amplitude of the modulating wave.

The percentage is defined as $\frac{B}{I} \times 100\%$. $I = \frac{I_m + I_t}{2}$

The above interpretation has been questioned by some authorities, but it is hard to explain the action of a modulated wave without some reference to it.

If the above explanation is true, the three components of the modulated wave can be considered to act separately. When the modulating wave is a pure sine wave, each sideband will be a wave of one definite frequency. It would be expected, therefore, that its amplitude would be proportional to the ordinate of the frequency response curve for that particular frequency. It was the purpose of this investigation to find out whether or not this relation was true.

The circuit was operated with a carrier of constant amplitude and constant frequency equal to 512 cycles per second. The amplitude of the modulating voltage (E_m) was kept constant but its frequency was varied. The oscillograph was placed in the antenna circuit and oscillograms were taken. Three typical cases are shown as plates 10, 11, 12. Measurements taken from all the oscillograms are shown in Table 2.

The following is a table showing measurements taken from the oscillograms (plates 9 to 16)

Table 2.

Plate No.	9.	10	11	12	13	14	15	16	
I_m in m.m.*	27.2	27.8	28.2	28.8	28.8	29.0	28.2	28.6	Measurements.
I_t in m.m.	8.6	7.8	7.8	8.0	8.0	8.0	8.0	8.0	
2B in m.m.	18.6	20.0	20.4	20.8	20.8	21.0	20.3	20.6	
$10 \times I_m/B$	29.3	27.8	27.7	27.7	27.7	27.7	27.9	27.8	
%Mod.	51.8	56.2	58.5	56.5	56.5	56.5	55.9	56.2 %	
B/2 (Osc)	.233	.250	.255	.259	.259	.265	.254	.257 amps.	Calculated.
B/2 (Curve)	.259	.259	.257	.252	.245	.237	.225	.196 amps.	
Freq. of E_m	4.	6.	8.	10.	12.	14.	16.	20. cycles/sec.	

See Fig 6d.

Im = Maximum ordinate on the modulated wave.

I_t = Minimum " " " " " .

$2B = I_m - I_t$

%Mod. = Percentage Modulation = $\frac{B}{I} \times 100\% = \frac{100\%}{\frac{I_m}{B} - 1}$.

B/2 (Osc) = B/2 taken from the oscillogram measurements above.

B/2 (Curve). = In this case B/2 was taken as 0.259 for the straight portion of the frequency-response curve, corresponding to a good value taken from the values of B/2 (Osc) from the line above. The other values of B/2 (curve) were calculated by assuming that they follow the relation shown in the frequency-response curve. The experimental and calculated values of B/2 are shown in Fig. 7.

* I_m and I_t are in millimeters. To change to amperes multiply by 0.05 .

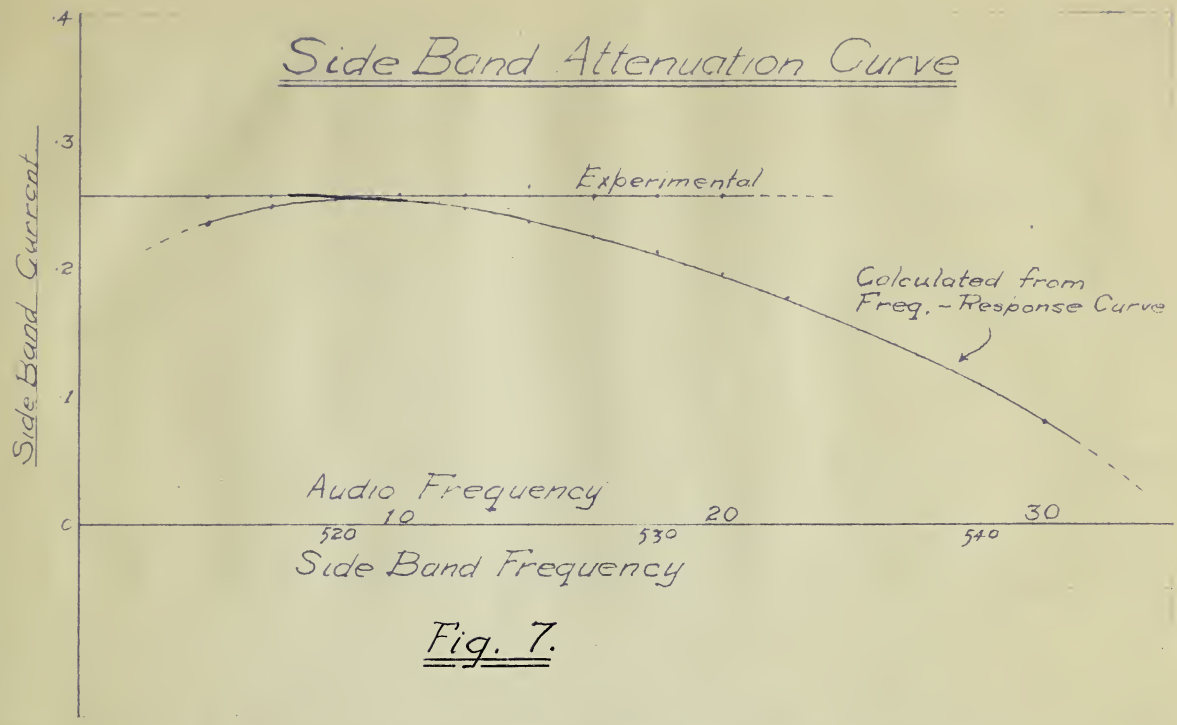

Side Band Attenuation Curve
Experimental
Calculated from
Freq. - Response Curve
Side Band Current
.4
.3
.2
.1
0
Audio Frequency
10
20
30
520
530
540
Side Band Frequency

Fig. 7.

These results show that the amplitudes of the sidebands and therefore the percentages of modulation are practically constant and do not vary in proportion to the ordinate of the frequency response curve. It must therefore be assumed that the antenna circuit, in this experiment, responded to the modulated imput as if it were a wave of approximately carrier frequency, and varying amplitude. Fig. 7 shows that when the modulating voltage has a frequency of 20 cycles per second, the experimental result differs from the theoretical by about thirty percent. This is the largest measured deviation. The results are therefore definately not in accordance with the generally accepted theory for the design of radio circuits. There is however no apparent reason why the circuit should not respond according to this theory.

The circuit differs from an actual radio circuit in some respects. For example,it is operated on a low frequency carrier and it has a decrement that is very high. There is nothing however in the theory to indicate that these factors should influence the results.

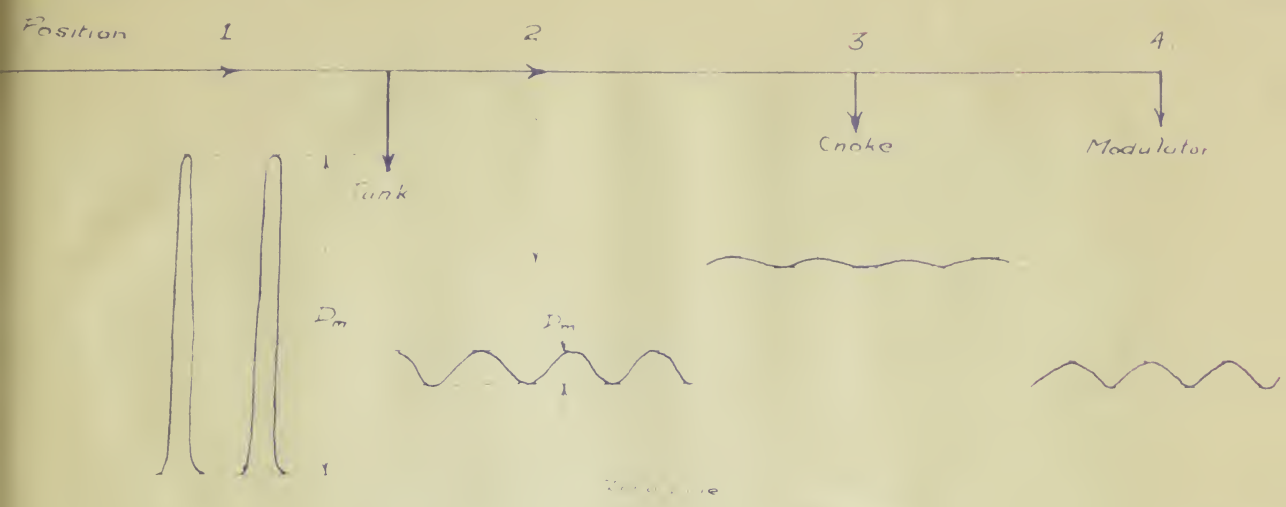
The interpretation of the geometric expansion of a modulated wave as being made up of three radio frequency waves of constant amplitude, does not seem to agree with the experimental results. Consequently, a thorough examination of the circuit was found necessary in order to determine the reason for the peculiar behavior.

With this object in view the circuit was operated, first with no modulating voltage, and then with different modulating voltages applied. Oscillograms of the currents in separate branches of the circuit were taken and analysed.

First, with the oscillator delivering a constant voltage and with no modulating voltage applied, the oscillograph was placed at positions 1, 2, 3, and 4 in the circuit, and the wave shapes that were viewed were traced out by hand. The oscillagraph was run at high speed in order to spread out the wave shapes as much as possible. Since it could not be operated fast enough to be synchronized to the 512 cycle wave, the wave shapes were not steady enough to photograph.

Fig. 4 shows the wave shapes obtained.

Fig. 4



CURRENT VALUES

Pos. No.	1.	2.	T.	3.	4.
D_m	141.2	18.0		4.0	14.0
I_m	70.6	9.0		2.0	7.0
I_{eff}	50.0	6.4	49.6	1.4	5.0
I_{dc}		46.0	0.	91.0	46.0

D_m was measured directly on the oscillograph.

$I_m = \frac{1}{2} D_m$ = the maximum value of the alternating current flowing.

$I_{eff} = \frac{I_m}{\sqrt{2}}$ = the effective value of the alternating current flowing.

The units are milliamperes.

Part 5. (Continued)

The distances from the zero line to the peak and trough of each wave were measured. The average of these two values gives I_{dc}.

A wave such as *is* found in position two may be considered to consist of

(a) A direct current I_{dc} found as above.

(b) An alternating current with maximum value I_m also found as above.

When combined these two will give a wave such as *is* found in position two.

The current in T was calculated by subtracting vectorially the current in pos. 2 from the current in pos. 1.

Note E_g will be considered the in-phase reference vector.

Then
Current in pos. 1 will be almost in phase.
" " " 2 " " " 90 lagging.
" " " T " " " in phase.
" " " 3 " " " 90 lagging.
" " " 4 " " " 90 lagging.

Description of the waves

Position No.

1. Rises almost perpendicular. Descends with a slant and curves slightly to the axis. Cutoff is at 180. degrees.

Part 5. (Continued)

Position No.

2. Practically a pure sine wave.

3. There is a very slight variation in the direct current through the choke, probably a sine wave variation.

4. In this wave the peaks are rounded and the bottoms slightly peaked, but it is a close approximation to a sine wave.

RESULTS

In position 1. the current is of the form to be expected, in the plate circuit of a class "B" amplifier. Such a wave may be analysed into a number of pure sine waves,- a fundamental and a number of harmonics. The frequency of the fundamental is the same as that of the input wave to the grid, and the amplidude is approximately equal to one half the maximum plate current.(D_m). This may be seen from an examination of the reference given. From this we see that I_m in pos. 1. is approximately 70.6 , as shown in the table.

Fig. 4. shows that all the current of frequency 512 cycles does not go into the output circuit; some of it is lost in the modulator circuit and the power supply. The current in the modulator circuit however is almost 90. degrees lagging, because of the high reactance of the choke in that circuit. The loss in the modulator circuit is negligible (0.05 watts compared to a loss of 7.9 watts in the output circuit). See next page *

Part 5. (Continued)

Results.

The D.C. in pos. 1 will be $D_m - I_m$ = 46.0 M.A.. The D.C. in pos. 3 (91.0) should equal the sum of the D.C. in pos. 2 and the D.C. in pos. 4. (46. + 46. = 92.0 M.A.). This D.C. was also measured in Exp't 1 and found to be 90.0 M.A.. These three values (91.0 , 92.0 and 90.0) check close enough to show that the preceding work with reference to D.C. currents at least, is correct.

The A.C. in pos. 2 (6.4 M.A.) should equal the A.C. in pos. 3 and the A.C. in pos. 4 (1.4 + 5.0 = 6.4).

Characteristic curves for the tubes were checked experimentally. The D.C. in pos. 1 and 4 were found to agree with the values as found from the characteristic curves.

In order to examine the effects in the circuit when a modulating voltage was applied, the circuit was arranged as shown in Fig. 1. The oscillator was tuned to 512 cycles. The values of E_m that were used are shown in the table following. The oscillograph was introduced into the circuit at various places, and oscillograms were taken. These are shown in the following pages.

ANALYSES OF THE OSCILLOGRAMS

Plate 2. The amplitude of this current is changed by the modulating wave. This current consists of,

(a) A steady D. C.

(b) An A. C. wave of complex form, consisting of a 512 cycle fundamental and its harmonics.

(c) An A. C. wave of low frequency, due to the modulating wave.

The value of the steady D. C. was found in Exp't to be 46.0 M. A.

Plate 3. This shows the current in position 2. This current consists of,

(a) A steady D. C.

(b) An A. C. wave of small amplitude. This represents the sum of the currents, of frequency 512 cycles, flowing in positions 3 and 4.

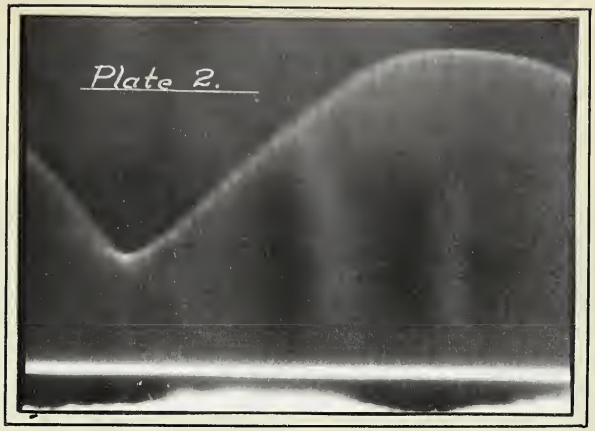


Plate 2.

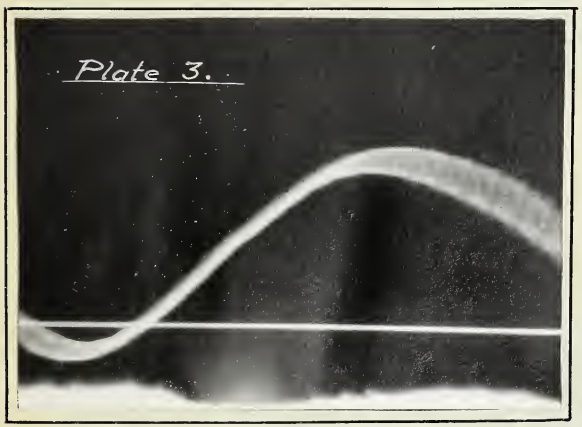


Plate 3.

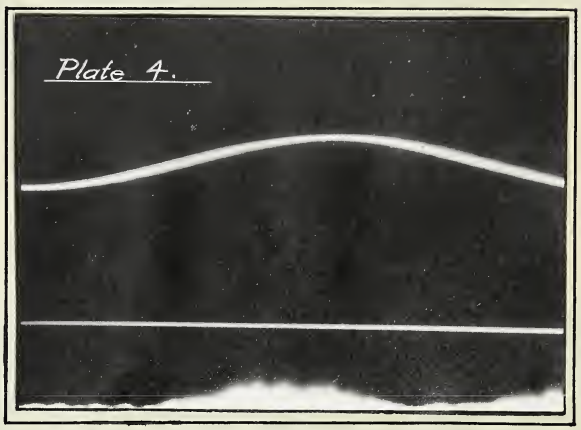


Plate 4.

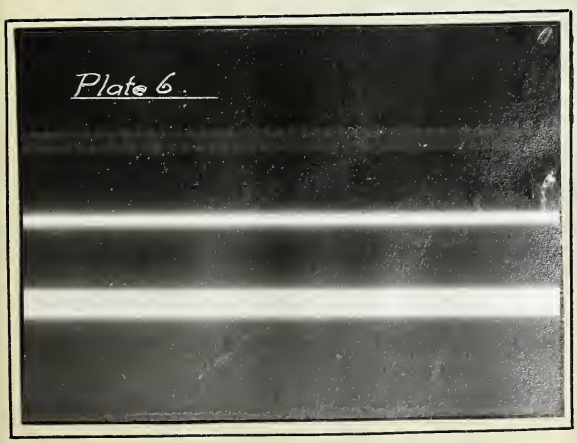


Plate 6.

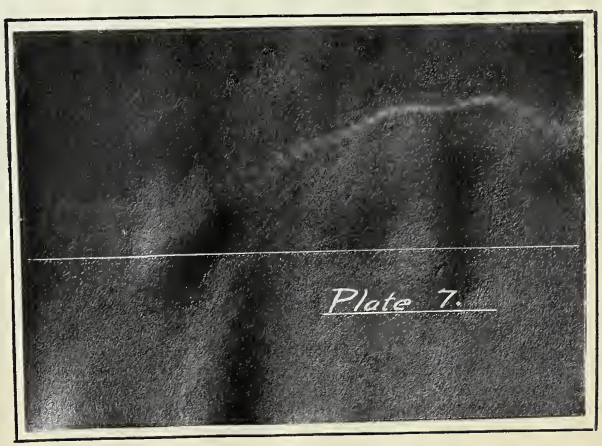


Plate 7.

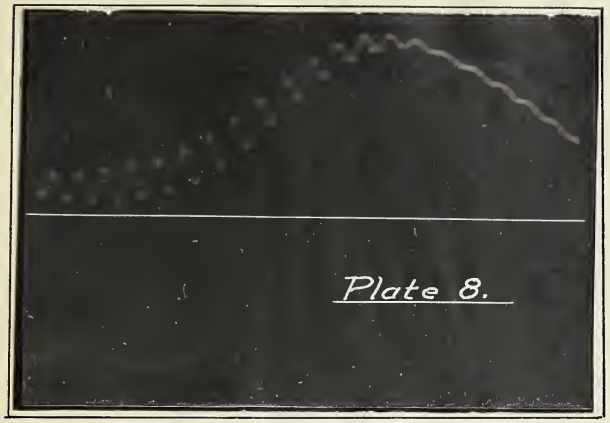


Plate 8.

Plate 10.

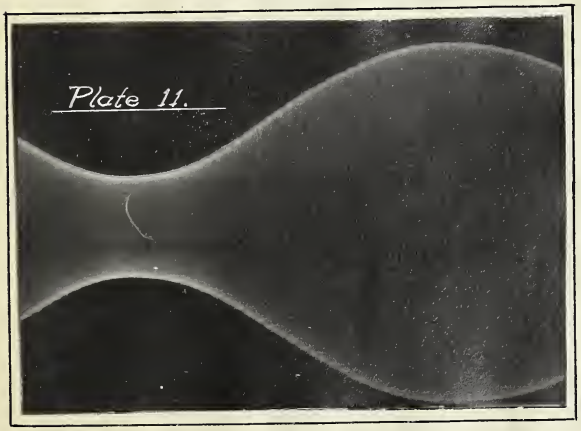


Plate 11.

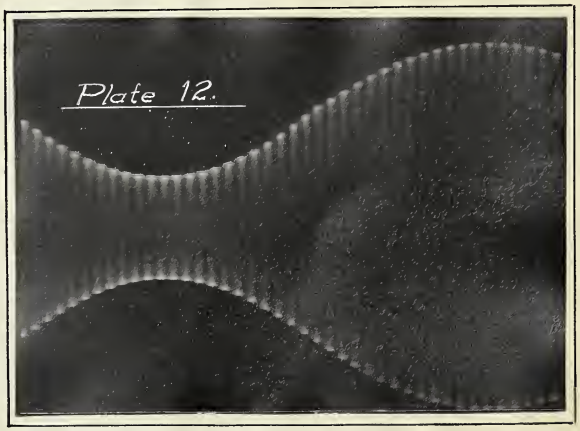


Plate 12.

Part 5 (Continued)

Plate 3.

(c) An A.C. of low frequency due to E_m.

The D.C. is 44.0 M.A. here, which checks fairly well with 46.0 (as found in Exp't. 2).

Plate 4.

This shows the current in the audio choke. It consists of,

(a) A steady D.C..

(b) A very small 512 cycle fluctuation. (Almost invisible on the oscillogram).

(c) An A.C. of low frequency due to E_m.

Plate 6.

The narrow center line is the zero line. The top wave is the current, of frequency 512 cycles, that is flowing in the modulator circuit. It consists of, -

(a) A steady D.C..

(b) A small A.C. of frequency 512.

The D.C. is 50.0 M.A., which checks with 46.0 M.A. (obtained in Exp't 2), and with the value obtained from the characteristic curve.

The A.C. is 4.2 M.A., which is of the same order as 3.8 M.A., which was obtained in the theoretical calculations in Part 4. For small currents such as these, better accuracy cannot be expected, because the lines in the oscillograms are from one to two milliamperes wide.

Part 5. (Continued.)

Plate 7. This is the same as plate 8, only the low frequency voltage and current are not sinusoidal.

Plate 8. This shows the current in the modulator circuit (position 4) . Except for a small variation, it is a sine wave the same as the voltage shown with it. It consists of, -

(a) A steady D.C..

(b) A small 512 cycle variation.

(c) A low frequency wave caused by E_m.

Plates 10 , 11 , and 12 belong to Exp't 4.

Below is a table of values showing measurements taken from the oscillograms.

Plate No.	1	2	3	4	5	6	8
Pos. No.	1	1	2	3	4	4	4
Freq.of E_m	10.	20.	20.	20.	20.	10.	20.
E_m(volts)	30.	30.	30.	30.	30.	0	30.
I_{mo}	206.4	203.2	104.0	120.0	108.0	56.0	108.0
I_t	72.8	71.2	-16.0	85.6	16.0	44.0	16.0
I_m	66.8	66.0	60.0	17.2	46.0	6.0	46.0
I_{eff},	47.2	46.7	42.4	12.2	32.5	4.2	32.5
I_{dc}			44.0	102.8	62.0	50.0	62.0
I_{av},	139.0	137.2					

The units are milliamperes.

Part 5. (Continued)

In the preceding table,

I_{mo} = The maximum ordinate on the alternating current wave. (From zero line)

I_t = The mimimum ordinate on the alternating current wave.

I_m = The maximum amplitude of the alternating current present.

I_{eff} = The effective value of the A.C. wave.

I_{dc} = The direct current present in the wave. This is calculated as the average value of the alternating current wave above the zero line.

I_{av} = The average value of the maximum amplitude of the A.C. wave above the zero line.

A study of the oscillograms as shown in the preceding pages shows that the separate branches of the circuit are operating in a normal manner. With the circuit tuned to resonance the values of current check with those calculated theoretically. There is no apparent reason why the circuit should act in anyway other than that indicated by generally accepted theoretical considerations.

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